

DESIGNING HUMAN-ROBOT COLLABORATION AS A JOINT COGNITIVE SYSTEM: A SOCIOTECHNICAL FRAMEWORK FOR MEANINGFUL WORK

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Abstract

Despite decades of research, construction robotics adoption remains limited due to unstructured environments, task complexity, and misaligned automation models adapted from manufacturing. Integrating insights from Joint Cognitive Systems (JCS), Meaningful Work research and Human-Robot Collaboration in construction studies, we propose an alternative, sociotechnical framework for robotic system design structured around three interdependent dimensions: (1) Task and Agent Design, which supports dynamic structuring, agent configuration, and time-based collaboration; (2) Coordination and Communication, which facilitates communication, coordination, shared mental models and situational awareness; (3) Worker Well-Being, which embeds physical and psychological safety, relatedness, competence and autonomy considerations.

Introduction

Research in construction robotics dates back to the 1980s and earlier, yet adoption still remains limited. This may suggest a mismatch between dominant automation models, largely derived from manufacturing, and key characteristics of construction work, including unstructured environments, high variability in tasks and materials, and reliance on situational judgment and embodied skill (Ardiny, Witwicki & Mondada 2015; Cai et al. 2019; Liu & Jebelli 2022; Saidi, Bock & Georgoulas 2016). As a result, models developed for standardised and predictable settings are difficult to transfer to construction contexts, that are difficult to formalise and therefore automate with the dominant model (Liu et al. 2024; Ardiny, Witwicki & Mondada 2015; Cai et al. 2019; Saidi, Bock & Georgoulas 2016). At the same time, labour shortages, safety risks, and an ageing workforce increase pressure for automation while complicating its implementation (Ranasinghe et al. 2023; Schwatka, Butler & Rosecrance 2012; Yamani Bin Yahya et al. n.d.). Human-Robot Collaboration (HRC) has recently gained attention as a way to enable robotic systems to operate in dynamic conditions through maintaining human involvement (Ma, Mao & Liu 2022; Onososen, Musonda & Ramabodu 2022; Zhang et al. 2023). However, many current frameworks still reproduce manufacturing-based models, such as levels of automation (LoA) taxonomies

and function allocation schemes derived from Fitts' List (Yang et al. 2024; Liang et al. 2021). This approach shows limited adequacy for the adoption in the industry (Du et al. 2025; Hancock & Scallen 1996) and has been linked to broader negative implications on societal well-being (Constantinides & Quercia 2025; Hancock 2014; Kaur, Gautam & Verma 2025). In other words, our current technology-centric mindset restricts the full potential of HRC and risks repeating earlier failures of construction robotics.

In this paper, we offer a way to reframe human-robot collaboration in the context of construction. We suggest the need to define HRC more broadly as "*humans working jointly with robots or together in a specific construction task, and each role must be capable of making contributions to the overall system.*" (Zhang et al. 2023) and shift towards a sociotechnical framework that acknowledges the complexity of the process and supports safe, meaningful work integrated into the realities of the industry.

To do this, our paper proceeds as follows. First, the background section introduces two key theoretical foundations: the Impact of Automation on Work Design and the Joint Cognitive System as a design unit. Second, the methods section introduces Critical Interpretive Synthesis, a methodology used. The results section presents this framework, structured around three interrelated HRC system design dimensions: task and agent design, coordination and communication, and worker well-being, and identifies key considerations for each based on Joint Cognitive Systems theory, meaningful work literature, and current HRC practices. Finally, the discussion and conclusion outline the framework, and discuss how it can be further developed and translated into practical tools for research and application.

Background

Impact of automation on work design

Understanding how automation reshapes work is key to designing human-robot collaboration. Each new technology redefines work processes yet many approaches still rest on the *Substitution Myth*, the belief that machines can take over human tasks without broader consequences for the system (Hollnagel & Woods 2005).

This view treats automation as a neutral replacement rather than a transformation of work. It appears mainly in two forms: the *Left-Over Principle* and the *Compensatory Principle*.

Left-Over Principle. The focus is on automating as much as possible, leaving humans with tasks that are either too trivial or too complex, rare, and irregular, often leading to cognitive overload (Woods & Hollnagel 2006). Since it's mainly developed without users in mind, it can also compromise safety, as workers develop workarounds that introduce new physical or organisational risks (Goštautaitė et al. 2024).

Compensatory Principle. This principle is based on juxtaposition; it is often referred to as “*Men-Are-Better-At, Machines-Are-Better-At*” or *MABA–MABA*, also known as *Fitts’ List* (Fitts 1951; Woods & Hollnagel 2006). It compares human and machine capabilities across fixed dimensions a-priori, assuming minimal variability and treating both as predictable systems. This approach also has safety implications. It often reduces human autonomy (Sadeghian & Hassenzahl 2022) and blurs responsibility, creating accountability gaps (Sadeghian, Uhde & Hassenzahl 2024). It also typically confines workers to supervisory or advisory roles with limited control, leading to alienation and difficulties in justifying the value of their work (Staaby, Hansen & Grønli 2021).

The question of meaningful human work design has become increasingly important with the growing automation of work. Organisational research on meaningfulness has developed two main perspectives: realisation and justification (Lepisto & Pratt 2017; Goštautaitė et al. 2024).

Realisation Perspective. The main focus is on fulfilling psychological needs such as autonomy, competence, and belonging. Meaningful work arises when individuals can express themselves through job design or job crafting, as described in Self-Determination Theory (Ryan & Deci 2000; Peters & Calvo 2023; Goštautaitė et al. 2024).

Justification Perspective. Here, meaningfulness is emerging through sense-making and reaffirming the significance of human contribution. It suggests that meaningfulness arises when people confront uncertainty about the value of their work, prompting sense-making processes shaped by leadership, organizational practices, and how performance is evaluated (Goštautaitė et al. 2024; Lepisto 2022; Beer, Micheli & Besharov 2022; Grant 2012). It draws on Honneth’s recognition theory (Honneth 1996), where recognition at work means acknowledging individuals as skilled contributors in cooperative activity, fostering self-confidence, self-respect, and self-esteem (Hirvonen & Breen 2020; Mardosas 2024).

Complementarity Principle. These psychological perspectives resonate with a third view on automation called the *Complementarity Principle*, introduced in the 1990s (Grote et al. 1995; Wafler et al. 2003). This principle examines work as a dynamic system that develops over time and aims to enhance human performance and learning instead of replacing it. Often

described as function congruence or function matching (Hollnagel 2018), it emphasises how work routines adapt to situational changes and seeks to maintain system performance across varying conditions (Woods & Hollnagel 2006). This principle becomes very useful for safety-critical industries like construction, which heavily rely on craft-based practice with workers at the center of decision-making.

Joint Cognitive System as a Design Unit



Figure 1: A figure contrasts the classical human–robot interaction view with the co-agency view across system boundary, temporal structure of action, and design focus

Joint Cognitive Systems (JCS) build on the complementarity approach and adopt a sociotechnical perspective, treating the practitioner as an integral part of the system. Developed in safety-critical domains such as aviation, nuclear power, and healthcare, JCS address the limitations of information-processing models by focusing on how systems maintain performance under changing conditions (Woods & Hollnagel 2006; Hollnagel & Woods 2005).

Classical Human-Robot Interaction (HRI) View. In the classical human–robot interaction view, humans and machines are treated as separate components connected through an interface. Interaction is defined as the exchange of inputs and outputs, as illustrated on the left side of Figure 1, where communication occurs through a bounded interface layer. Cognition is modeled as a response to discrete stimuli, and action is understood as a sequence of stepwise reactions. The analytical focus remains structural, describing system components and their interactions rather than how the system performs as a whole.

Limitations of the Classical View. This representation abstracts away key characteristics of real-world work. It treats action as discrete rather than continuous, and behavior as reactive rather than anticipatory. Context is reduced to inputs, rather than directly shaping action, and cognition is effectively placed outside of its situated environment. It also assumes isolated actors, while in practice human activity is embedded in broader systems of coordination. As a result, the design focus remains on interfaces and components rather than system-level performance.

Co-Agency View (JCS). JCS shifts the focus from interaction to co-agency, understood as joint agency within a single system. As shown on the right side of Figure 1, humans and machines are physically separate, but physical separateness does not imply functional

separateness. The unit of analysis becomes the joint system, engaged in continuous cycles of sensing and responding. The focus moves to what the system achieves as a whole, and how it adapts under changing conditions. Behavior is continuous and context-dependent, and agency is distributed across human and machine.

Critical interpretive synthesis (CIS)

This study employs Critical Interpretive Synthesis (CIS), a method first developed in medical research (Dixon-Woods et al. 2006) and later adapted for the built environment and construction automation (Bucher et al. 2024; Pan et al. 2018). CIS combines review and interpretation, using induction and critical reflection to identify conceptual patterns, making it suitable for developing theoretical frameworks that connect diverse perspectives.

After preliminary scoping, we conducted three targeted Scopus searches: (1) human–robot collaboration (HRC) in construction (272 records), (2) Joint Cognitive Systems (JCS) (144 records), and (3) meaningful work (MW) in automation contexts (45 records). After screening, studies without a human-in-the-loop or not related to construction were excluded from the HRC set, overly technical papers from the JCS set, and superficial human factors studies from the MW set. This resulted in 74 HRC, 39 JCS, and 21 MW papers, further reduced through full-text review to 38 HRC, 22 JCS, and 14 MW studies. Two foundational JCS books were also included (Hollnagel & Woods 2005; Woods & Hollnagel 2006).

The synthesis proceeded iteratively in three steps. First, the HRC literature was analysed inductively to identify recurring patterns in how collaboration is studied in construction. The review revealed a fragmented, largely technology-centric field dominated by experimental studies and demonstrators, with limited attention to real-world adoption and an underdeveloped account of the human role. This lack of implementation-oriented research motivated the search for a stronger theoretical foundation.

Second, these limitations led to the selection of Joint Cognitive Systems (JCS) as the primary theoretical foundation, as it provides a systems perspective grounded in safety-critical domains with established real-world use. Third, meaningful work research was incorporated to extend this foundation with a more direct account of the human dimension, particularly longer-term work design and its impact on workers.

The framework was then defined by adapting JCS to the context of human–robot collaboration in construction, with meaningful work as a complementary perspective. The construction HRC literature was used to ground this adaptation, guiding the selection and alignment of concepts based on current developments, observed gaps, and practical constraints in the field.

Dimensions of human-robot collaboration (HRC) system design

This framework is a conceptual, high-level structure for human–robot collaboration system design in construction, intended for system designers, engineers, and researchers working at the level of system configuration and integration. It structures how work, coordination, and human factors are addressed together when designing joint human–robot work systems at the level of sociotechnical system architecture.

The framework is organised around the core components of human–robot collaboration: humans, robots, and their collaboration. Task and Agent Design focuses on work, addressing task structure and role configuration. Coordination and Communication focuses on the robotic system and its role in enabling joint activity, addressing sensing, interaction, and control. Worker Well-Being focuses on the human, addressing longer-term work conditions and their impact.

The dimensions are tightly interconnected and operate as system-level design lenses. Figure 2 shows their cyclical relationship: they are not ontologically separate components, but purpose-driven perspectives used to guide system design. Coordination and Communication is positioned centrally because the robotic system acts as the mediating and coordinating layer through which joint activity is organised, linking work processes and worker conditions.



Figure 2: Three main interrelated human-robot collaboration (HRC) system design dimensions.

Task and agent design

Task design. To design a system, its boundaries must first be defined by distinguishing between the system and its environment. Since control, both in goals and variability, occurs at multiple levels, several joint cognitive systems can coexist (Hollnagel & Woods 2005). In construction, task design concerns what needs to be built and how it is divided into levels or subtasks based on granularity and scope. For example, scaffolding construction can be broken down into subtasks, steps, activities, and fine-grained task primitives (Pan & Yu n.d.). Integrating these task hierarchies into management workflows and related cognitive systems is essential. It is also important to consider not only direct but also indirect and off-task work (Van Diggelen & Johnson 2019), which often increases with automation, and to allow for dynamic adaptation when conditions change.

Dynamic task restructuring. Adaptation in a successful HRC system goes beyond allocating tasks based on human and robotic skills (Amtsberg et al. 2021). It also involves restructuring tasks and goals. Shifting objectives, refining standards, and enabling workers to shape tasks are central to meaningful work. This approach fosters ownership, responsibility, and helps prevent accountability gaps and alienation (Parmer 2024; Sadeghian, Uhde & Hassenzahl 2024; Staaby, Hansen & Grønli 2021; Mardosas 2024; Bielskis 2024; Smids, Nyholm & Berkers 2020; Celentano 2024). JCS studies highlight the importance of directability, the ability to assess and modify the actions of others in a joint activity as conditions evolve (Klein et al. 2004). In construction, this remains underdeveloped. One study addressed human control through a digital twin that visualises both the work object and the robot's motion plan (Amtsberg et al. 2021). The craftsman in the study can take over a task at any time in case of material inconsistencies, path collisions, or other unforeseen issues. Bidirectional communication and real-time visualisation support informed decision-making for timber handling.

Time-based collaboration design. Human-robot collaboration is inherently time-based, and construction management traditionally depends on distinct phases and scheduling. HRC design should acknowledge this temporality and the continuously shifting relationships between human and robotic actors. Instead of fixed roles, collaboration can be viewed as a sequence of shifting team patterns depending on task, state, and context. Common team patterns between humans and intelligent systems (Van Diggelen & Johnson 2019) include synchronous joint work, synchronous asymmetric work such as monitoring or teleoperation, and mixed modes that combine synchronous pre-planning with asynchronous execution. These patterns involve transitions and handoffs as activities progress and are interdependent with neighbouring ones. In practice, even highly autonomous modes remain embedded within broader human oversight and system interdependencies. The highly autonomous pattern is one among several interconnected patterns, implying a human backup role that requires continuous monitoring and readiness to intervene. In construction, this aspect remains underdeveloped as well. Most HRC studies prototype only one activity type, usually synchronous, focusing on physical interaction or teleoperation.

Agent design. In order to stay purpose-driven and goal-oriented, robotic agents should be seen as functionally integrated extensions of human capabilities rather than separate tools (Hollnagel & Woods 2005). From a JCS perspective, all work is cognitive, but for practical design, it is helpful to view the robotic agent as combining a machine and a computer, which are tightly coupled. This corresponds to the dual nature of construction work, where physical activity involves manipulating tangible materials and cognitive activity involves perception and information processing. In timber prefabrication, human and robotic skills can be grouped into manipulation and mobility, with humans contributing dexterity and robots

providing precision and strength (Yang et al. 2024). Cognitive skills include situation awareness, decision-making, motion planning, and adaptation. In masonry, robots can take over repetitive lifting and bricklaying, allowing workers to focus on detailed finishing tasks (Baek et al. 2024). These examples show that agent selection must always be grounded in the specific capabilities required by each construction activity and seen as evolving over time.

Coordination and communication

Communication channels. An important part of human-robot collaborative co-agency is communication. Instead of viewing the interface as a piece of technology, the system can be understood through coordination and the flow of information between agents as the basis for effective collaboration. Human-to-robot communication can rely on gesture, voice, gaze, bio-signal, and vision-based commands or manual controllers, including haptic master devices, AR, and multiple sensors such as EEG (Liu & Jebelli 2022; Zhang et al. 2023). For other communication channels, the technology should be chosen or designed accordingly. For example, in on-site construction scenarios, robot-to-human communication can be embedded in wearables such as wrist-mounted displays or helmet indicators, and robot-to-environment communication can use simple machine-based indicators (Frank et al. 2019). These channels together provide essential infrastructure for coordination, but do not replace coordination design itself.

Multi-modal coordination. Support for effective coordination is one of the generic requirements for designing a joint cognitive HRC system. It involves synchronising agents in changing conditions, creating and updating a shared mental model, balancing goals, and ensuring observability (Woods & Hollnagel 2006). In practice, coordination should provide not only feedback, which is common, but also feedforward and feednow. In the Extended Control Model (ECOM), these correspond to control layers such as tracking, regulating, monitoring, and targeting (Hollnagel & Woods 2005). Integration with Building Information Modelling (BIM), the Internet of Things (IoT), digital twins, and other advanced technologies provides an additional coordination and data-processing layer within the joint cognitive system. (Amtsberg et al. 2021; Zhang et al. 2023).

Effective coupling. In HRC new qualities emerge through human-robot coupling or their interrelations (Hollnagel & Woods 2005). Human-robot coupling is crucial since inadequate cognitive coupling results in poor user acceptance (Woods 1985). Effective coupling and systems that remain viable over time require involving construction workers early in system design, well before implementation (Fraboni, Brendel & Pietrantoni 2023; Staaby, Hansen & Grønli 2021; Celentano 2024). This can be achieved through prototyped VR-based environments that provide low-cost, safe tools integrating simulation, ergonomic analysis, and embodied feedback to refine interaction, coordination, and workflow design

(Onososen & Dzuwa n.d.; Saffert et al. 2024; Onososen et al. 2023). These tools also act as methodological environments for exploring team dynamics with continuous human feedback.

Shared mental models and situation awareness. Effective coupling can be further improved through shared mental models, system transparency, and mutual observability. System transparency enhances explainability and helps prevent accountability gaps (Sadeghian, Uhde & Hassenzahl 2024). Maintaining shared mental models and situational awareness requires integrating multiple communication and processing threads. For dynamic environments such as on-site construction, integrating multi-sensory channels has shown promising results for human–robot collaboration (Zhang et al. 2023). This reflects real construction situations where workers routinely use multiple modes of communication, such as eye contact, gestural confirmation, and verbal exchange, especially before entering potentially hazardous areas near equipment (Frank et al. 2019).

Affordance and resilience. Beyond coordination and miscoordination, affordance and resilience are two main patterns that emerge at the intersection of people, technology, and work (Woods & Hollnagel 2006), and therefore should be explicitly addressed in HRC system design. In a study from Switzerland, construction and mining workers expressed similar views on what future automation should provide. They emphasised adaptation to changing situations and the facilitation of collaboration in all work contexts as fundamental requirements (Frank et al. 2019).

Worker well-being

Physical and psychological safety. Worker well-being is treated not as an external ethical constraint but as a constitutive condition and affordance for joint system performance. This includes strategic choices such as using teleoperation in high-risk scenarios (Zhang et al. 2023) or adjusting robot speed and working parts based on a worker's cognitive load (Liu & Jebelli 2022). Good practices include demonstrating safety and reliability, involving workers in hazard analysis, and applying explainable mechanisms that clarify system goals and reasoning (Fraboni, Brendel & Pietrantoni 2023; Sadeghian, Uhde & Hassenzahl 2024). Avoiding unrealistic expectations about communication or capability is equally important, as unmet expectations can harm team dynamics (Sadeghian & Hassenzahl 2022).

Relatedness and team composition. The question of socio-cognitive misalignment also arises when designing human-robot collaboration in relation to the need for human connection. Robots can successfully cooperate to achieve shared goals, yet they are not equivalent to human colleagues due to differences in social interaction, informal communication, and behaviour in safety-critical situations (Nyholm & Smids 2020). Social relationships remain fundamental for meaningful work and self-development (Sadeghian & Hassenzahl 2022; Staaby,

Hansen & Grønli 2021; Smids, Nyholm & Berkers 2020; Nikolova, Cnossen & Nikolaev 2024). Interviews with timber construction workers consistently highlighted three key motivators: the joy of building, task variety, and teamwork (Yang et al. 2024). In the HRC system design, social connection must be explicitly supported.

Competence and expertise creation. A further human-centered goal in HRC system design is continuous learning for both human and robotic agents. This includes the refinement of standards, open-ended rather than predefined automation loops, and the active development of skills and self-growth (Parmer 2024; Sadeghian & Hassenzahl 2022; Staaby, Hansen & Grønli 2021; Smids, Nyholm & Berkers 2020; Celentano 2024; Graham & Jones n.d.). The system itself can learn and adapt through methods such as Robot Learning by Demonstration, Imitation Learning, or programming by demonstration, which enable robots to acquire complex construction skills (Liang et al. 2021). At the same time, embedded training modules and interactive systems can help workers strengthen their expertise and develop new interaction skills (Onososen & Dzuwa n.d.; Saffert et al. 2024; Shayesteh et al. 2023). This fluid, adaptive approach to expertise creation within co-agency can address workforce challenges in the construction industry.

Autonomy and job crafting. Continuous learning and adaptation also strengthen personal autonomy and its recognition in work design. Limiting human roles to supervision or advisory functions can fragment ownership, reinforce alienation (Staaby, Hansen & Grønli 2021), and create authority–responsibility double binds, where workers are accountable but unable to exercise real autonomy (Sadeghian, Uhde & Hassenzahl 2024; Woods & Hollnagel 2006). HRC systems should enable agency, feedback, and flexibility, fostering a sense of ownership and purpose (Parmer 2024; Sadeghian, Uhde & Hassenzahl 2024; Sadeghian & Hassenzahl 2022; Staaby, Hansen & Grønli 2021; Mardosas 2024; Bielskis 2024; Smids, Nyholm & Berkers 2020; Nikolova, Cnossen & Nikolaev 2024; Graham & Jones n.d.). This aligns with ethical design principles that emphasise privacy, autonomy, dignity, reliability, inclusion, and the right to choose one's own way of working (Kaasinen et al. 2022). HRC systems need to maintain open-ended structures that allow roles and tasks to be shaped dynamically. Job crafting should be treated as an active process of person–job fit, with explicit goals to support meaningful work and to avoid the Psychologist's Fallacy, which is the mistake of confusing the designer's or observer's vision of work with the lived experience of those who actually perform it (Staaby, Hansen & Grønli 2021; Woods & Hollnagel 2006).

Discussion

Prior human-robot collaboration (HRC) frameworks in construction (Yang et al. 2024; Liang et al. 2021) build on concepts from manufacturing and industrial automation, particularly Levels of Automation, function allocation, and Human–Robot Interaction (HRI) taxonomies, providing a structured basis for describing roles,

interactions, and system configurations under relatively stable, fixed, a priori conditions. This paper reframes HRC as a sociotechnical and temporal process in which human and robotic capabilities, fragmented organisational structures, shifting teams, and evolving site conditions co-adapt. It considers how responsibility shifts, how expertise is negotiated, and how coordination can be maintained under changing conditions.

It does so by redefining the unit of design from interfaces or separate human and robot agents to a joint cognitive system. This shifts the focus from task allocation to coordination of work, from static levels of autonomy to continuous co-adaptation, from isolated interaction variables to system-level performance, from describing and classifying parts or configurations to designing purpose-driven systems oriented to performance, adoption, and meaningful work.

From this perspective, construction robotics can move from being “robot-ready”, organised around machine capabilities, to “system-ready”, where task structures, communication flows, and organisational roles support joint performance.

Future research should further develop this framework into more explicit design-oriented structures that can guide system design. The current considerations define key domains and relationships but remain conceptual. They need to be translated into forms that inform task decomposition, role configuration, coordination, and system design. Empirical work in real construction settings is required to examine how these considerations support implementation, adaptation, and adoption in practice.

Conclusions

This paper synthesises insights from Human–Robot Collaboration (HRC) in construction, Joint Cognitive Systems (JCS), and Meaningful Work (MW) research to propose an integrated framework for HRC system design. The framework is structured around three interdependent dimensions: (1) Task and Agent Design, which addresses multilevel task design, dynamic task restructuring, agent design, and time-based collaboration design; (2) Coordination and Communication, which focuses on communication channels, multi-modal coordination, effective coupling, shared mental models, situational awareness, affordance, and resilience; and (3) Worker Well-Being, which emphasises physical and psychological safety, relatedness and team composition, competence and expertise creation, autonomy, and job crafting.

Grounded in Joint Cognitive Systems (JCS) theoretical framework with added perspective from Meaningful work (MW) scholarship, the proposed conceptual framework reframes construction Human-Robot Collaboration (HRC) as a joint cognitive system in which performance, safety, learning, and accountability emerge from the quality of coupling across people, robots, and work over time. The paper shifts the design problem from “who does

which task” to “how joint work is structured, coordinated, and sustained without degrading human work.” Future research will extend the framework into HRC system design and engineering tools for construction robotics projects.

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